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14. ABSTRACT

On our 31st trip to the laser facility at WSMR we carried out experiments on laser ablation of black and white Delrin [also called polyoxymethylene, polyformaldehyde, $(HCHO)x$]. Mass ablation and thrust generation (Impulse) were accurately measured as a function of input laser energy in one shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on the geometry of the energy absorption/conversion zone. The most ideal geometry, an axis symmetric mini thruster, produced ~ 60 % conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced ~ 50% conversion efficiency. The upper limit to energy conversion was computed with CEA code to be 73% for the well defined mini thruster geometry. Thus, total losses amount to ~ 13% and ~ 23%. This is a significant finding and helps to validate the concept of "momentum calorimetry", in which experiments like those accomplished here may be conducted to obtain reliable heats of formation. The performance of candidate chemically enhanced laser ablation or other solid propellants may be measured on a small scale. In these most recent experiments, a near-exact match of coupling coefficients (1%) was achieved in a 14-fold scale-down of the 10-cm Lightcraft to the mini thruster.

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Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster

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Abstract. Experiments on laser ablation of black and white Delrin® with a 10.6-micron laser beam from a CO_2 electric discharge laser are reported. Mass ablation and thrust generation (impulse) were accurately measured as a function of input laser energy in single-shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on the geometry of the energy absorption/conversion zone. The standard geometry, an axisymmetric mini-thruster with 13-degree conical half angle and 8:1 expansion ratio, produced ~65 % conversion efficiency. The extensively-studied 10-cm focal diameter Lightcraft (with inverted paraboloid, plug-nozzle geometry) produced ~50% conversion efficiency. The upper limit to energy conversion was theoretically computed with a one-dimensional chemical equilibrium code to be 73% for the well-defined mini-thruster geometry. Thus, total losses amount to ~8% in the mini thruster and ~23% in the Lightcraft. In these experiments a near-exact match of coupling coefficients, ~1%, was achieved in a 14-fold scale-down of the 10-cm focal diameter Lightcraft to the mini-thruster. These results helped validate the concept of "momentum calorimetry" in which heats of formation of energetic propellants are obtained by measurement of the momentum of the jets they produce when they are ablated with known laser energy. The performance of chemically-enhanced laser ablation propellants or other solid propellants may be inexpensively measured on a small scale. A matrix of impulse measurements, ablated mass, laser energy and plume absorptivity was carried out with various mini-thruster expansion ratios and chamber geometries.

Keywords: Laser; Ablation; Lightcraft; Delrin®; mini-thruster; calorimetry; pendulum
PACS: 06.20.Dk; 06.30.Dr; 06.30.Gv; 07.05.Fb; 07.05.Hd; 07.05.Kf; 07.10.I.w

INTRODUCTION AND OBJECTIVE

A series of experiments were conducted by the Propulsion Directorate of the Air Force Research Laboratory (AFRL) at Edwards AFB, CA to evaluate the performance of different propellant combinations for use with the Experimental 25-cm Focal Diameter Laser Ramjet/Rocket (X-25LR). In the past, the primary propellant proposed for the rocket phase of vehicle flight was white Delrin®, a form of solid formaldehyde. Experiments conducted using the Pulsed Laser Vulnerability Test System (PLVTS) at the High Energy Laser Systems Test Facility (HELSTF) at White Sands Missile Range (WSMR), NM yielded Delrin® performance characteristics with coupling coefficient, C_m, of approximately 450 N/MW and specific impulse, I_{sp}, of approximately 300 seconds.

It was recently proposed that additional propellant formulations and geometries should be evaluated including black Delrin®, a series of propellant combinations that integrated energetic fuels such as ammonium nitrate (AN) and ammonium perchlorate (AP) and Delrin® geometries that increased the amount of surface area that would be

ablated by the laser pulse. The measurements taken for the mini-thrusters were compared with the well-defined and extensively-studied characteristics of the 10-cm focal diameter Lightcraft.

Mini-Thrusters and Ballistic Pendulums

In order to quickly and inexpensively evaluate these propellant combinations and geometries, a collection of miniature axisymmetric thrusters with 13° half-angle conical nozzles were designed and fabricated. These mini-thrusters varied in their combustion chamber geometries and expansion ratios. The typical geometry, however, was an 8:1 expansion ratio with a short combustion chamber. Additional geometries included 16:1 expansion ratios and long combustion chambers and all possible combinations of those four variables. Schematics of the 8:1 and 16:1 expansion ratios are shown in Figure 1.
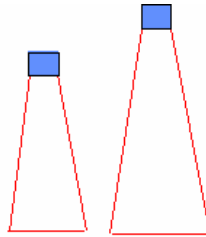

FIGURE 1. Mini-Thruster Schematics: 8:1 Expansion on Left; 16:1 Expansion on Right

Some specific parameters regarding the 8:1 expansion ratio mini-thruster are as follows: mass = 7.8 grams; propellant surface area ≈ 0.71 cm^2; propellant mass ≈ 0.64 grams.

Additionally, two new ballistic pendulums were fabricated specifically for the mini-thruster geometry. One pendulum was solid aluminum with a square cross-section and the second was a similar geometry, but with a significant amount of material removed from the square cross-section to reduce the mass of the pendulum. The addition of this second pendulum provided the opportunity to investigate and compare the sensitivity and accuracy of the two pendulums.

The ballistic pendulum system consists of the pendulum itself, on which the mini-thrusters or Lightcraft are mounted, a rotating potentiometer to measure the amount of angular displacement of the pendulum when the vehicle is impacted by the laser pulse and an accelerometer or "impulse hammer", which is used to calibrate the level of angular displacement with the level of impulse imparted to the vehicle.

10-cm Focal Diameter Lightcraft

As stated above, the 10-cm focal diameter Lightcraft has been often and extensively studied by the USAF as an experimental precursor to the X-25LR, which is to be used for launches to Low Earth Orbit (LEO). A schematic of the vehicle is shown in Figure 2. Some parameters of the vehicle are: expansion ratio = 14; mass = 40 grams including propellant; propellant surface area ≈ 25 cm^2; propellant mass ≈ 10

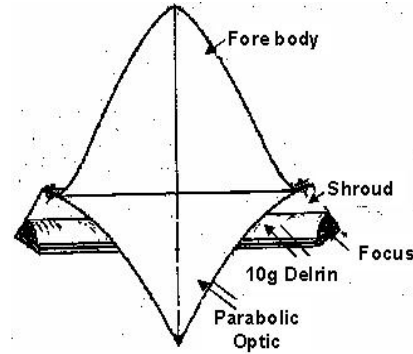grams; and Thrust-to-Weight Ratio of 11.0 at laser power, $P_l = 10$ kW with white Delrin® propellant.

FIGURE 2. Schematic of 10-cm Focal Diameter Lightcraft

The performance parameters associated with the 10-cm focal diameter Lightcraft which are used as a basis of comparison for the mini-thrusters are: $C_m = 450$ N/MW, exhaust velocity, $V_e = 2270$ m/s; propulsive efficiency = 51%; propellant specific energy, $E_l/m = 5.1$ MJ/kg; and a laser power per unit area of 0.8 MW/cm².

Conversion of Laser Energy to Jet Kinetic Energy [1]

To determine the efficiency of conversion of laser energy to jet kinetic energy, one must begin with the specific internal energy of the propellant, Q^*, the kinetic energy of the exhaust, E_{jet}, and the impulse, I,

$$Q^* = \beta E_l/m_p \tag{1}$$
$$E_{jet} = \tfrac{1}{2} m_p <v_e^2> = \alpha m_p Q^* = \alpha\beta E_l \tag{2}$$
$$I = m_p <v_e> \tag{3}$$

where β is the absorption efficiency, m_p is the propellant mass, E_l is the laser-pulse energy, $<v_e^2>$ is the average of the square of the exhaust velocity, α is the expansion efficiency and $<v_e>$ is the average exhaust velocity. Then,

$$I^2/2m_pE_l = \alpha\beta<v_e>^2/<v_e^2> = \alpha\beta\Phi \tag{4}$$

where Φ is defined as $<v_e>^2/<v_e^2>$ and $<v_e>^2$ is the root-mean-squared (rms) velocity of the exhaust. Now, taking the definition of the coupling coefficient,

$$C_m = I/E_l = 2\alpha\beta/<v_e>[<v_e>^2/<v_e^2>] = 2\alpha\beta\Phi/<v_e> = [m/E_l]\ v_e \tag{5}$$

Therefore,

$$\tfrac{1}{2}\ C_m <v_e> = \alpha\beta\Phi \tag{6}$$

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If the propellant used has been infused with energetic materials, the right side of the previous equation is,

$$(\alpha\beta\Phi)_{apparent} = \alpha\Phi(\beta + m_p\Delta u_{chem.}/E_l) \qquad (7)$$

where, $\Delta u_{chem.}$ is the specific internal energy of the propellant due to chemical reactions.

Experimental Plan

The experimental plan for the most recent series of experiments conducted at HELSTF in WSMR, NM in December of 2004 centered on the evaluation of a series of mini-thrusters with air, white and black Delrin® as propellants. In addition, these values were compared to the experimental values obtained for the same propellants in the 10 cm focal diameter Lightcraft.

The laser at HELSTF is a 10 kW, 10.6 μm, CO_2, pulsed, electric-discharge laser that was fired in the far-field with a portion of the beam blocked to control the incident laser energy for the mini-thruster experiments and the near-field for the 10-cm focal diameter Lightcraft.

15 separate mini-thrusters were considered: five with black Delrin®; five with white Delrin®; and five with air as propellant. Each of the 15 mini-thrusters was weighed prior to the experimentation and then each of the 15 mini-thrusters was shot five times at a different laser-pulse energy ranging from 8 J/pulse to 25 J/pulse. After the five shots, the mini-thrusters were weighed again and an average propellant ablation mass was determined.

The exhaust velocity can then be determined using Equation 8, the coupling coefficient can be determined using Equation 9 and the efficiency can be determined using Equation 10,

$$v_e = I/m \qquad (8)$$
$$C_m = I/E_l \qquad (9)$$
$$\eta = I^2/2m \qquad (10)$$

These three quantities were evaluated for all 75 shots that were taken and then compared with one another. In addition to this data, digital photographs were taken of each of the laser shots to visualize the exhaust plume and its characteristics.

An identical set of experiments were conducted for the 10 cm focal diameter Lightcraft with the exception of the fact that there is only one vehicle, so the vehicle was weighed after every five-shot set at each laser-pulse energy and then the propellant inserts were changed. The laser-pulse energies in question ranged from 90 J/pulse to 400 J/pulse. The performance and efficiency of the 10-cm focal diameter Lightcraft was then compared with all of the mini-thrusters, as were the digital photos of the exhaust plume.

RESULTS AND DISCUSSION

Mini-Thruster Experiments

The experimental results from the mini-thruster tests were as predicted in some ways and completely unexpected in other ways. For instance, as expected, the performance values for air as a propellant were considerably less than black or white Delrin®. However, it was thought that the black Delrin® would yield a much higher exhaust velocity than the white Delrin® because the authors thought that the color of the propellant would have some effect on the efficiency of the absorption of laser energy or the absorption depth. This did not appear to be the case, as can be seen in Figures 3 – 7, where the curves for white and black Delrin® lie virtually on top of one another. In addition, there is an odd trend that occurs when using all propellants as the laser-pulse energy increases. One would expect both the coupling coefficient and the exhaust velocity to increase as laser-pulse energy is increased, assuming that the absorption depth and efficiency remain the same. This obviously is not the case. In Figure 3, the value of coupling coefficient declined over the range from 8.7 J to 12.0 J, increased from 12.0 J to 17.4 J, and then stayed relatively constant at 400 and 450 N/MW from 17.4 J to 24.9 J. This trend is the same for both black and white Delrin®, with a less pronounced trend for the air as a propellant. A similar trend can be seen in the values of propulsive efficiency shown in Figure 5.

On the other hand, the values for exhaust velocity, shown in Figure 4, appear to be as expected with a continual increase in values as the laser-pulse energy was increased. An alternate explanation could be found in the values for the specific energy of the propellant due to the laser pulse, E_l/m. According to Table 1, a table of the average performance values for the mini-thruster experiments, and Figure 6, a graph of the Table 1 values, the value of E_l/m, elevates considerably from 5.3 MJ/kg to 8.22 MJ/kg for black Delrin® and 5.51 MJ/kg to 8.33 MJ/kg for white Delrin® as the laser-pulse energy is increased from 8.7 J to 12.0 J. According to Larson, et al [2], this results in higher I_{sp} with a lower coupling coefficient.

Figure 7, a graph of mass loss vs. laser-pulse energy, is derived from the previous four figures. Mass loss declines only slightly from 8.7 J to 12.0 J, which is in agreement with Figures 3 and 4, in which the coupling coefficient was reduced drastically while the exhaust velocity increased. The mass loss then increased dramatically throughout the rest of the range of laser-pulse energies, as the exhaust velocity continued to increase gradually or remain constant while the coupling coefficient increased dramatically between 12.0 and 17.4 J and then remained relatively constant.

Figure 8, digital photos of the exhaust plumes of the mini-thrusters, is interesting, as well. The left column shows the exhaust plume for the mini-thrusters with air as a propellant. The only noticeable plume appeared to be a vivid white light emanating from the interior of the mini-thruster. This is most likely a flash from the air detonation resulting from the incident laser energy. The middle column is for the white Delrin® propellant. The exhaust plume in these cases was red in color and

nearly transparent. The right column is for the black Delrin® propellant. The plume in these cases was noticeably more orange, likely an effect produced by the additional carbon components in the exhaust igniting after evacuating from the mini-thruster.

TABLE 1. Average Performance Values for Mini-Thruster Experiments

| Propellant	EL(J)	Cm(N/MW)	I(Ns)	m(g)	Ve(m/s)	Eff	EL/M (MJ/kg)
black	8.7	385	0.00335	1.64E-03	2044	0.39	5.30
black	12.0	265	0.00317	1.46E-03	2175	0.29	8.22
black	17.4	451	0.00785	2.70E-03	2909	0.66	6.44
black	21.0	438	0.00920	3.28E-03	2806	0.61	6.40
black	24.9	434	0.01080	3.80E-03	2847	0.62	6.55
white	8.7	373	0.00325	1.58E-03	2055	0.38	5.51
white	12.0	268	0.00321	1.44E-03	2232	0.3	8.33
white	17.4	444	0.00772	2.76E-03	2799	0.62	6.30
white	21.0	418	0.00878	3.20E-03	2743	0.57	6.56
white	24.9	428	0.01070	3.58E-03	2977	0.64	6.96
air	8.7	236	0.00206				
air	12.0	161	0.00194				
air	17.4	240	0.00417				
air	21.0	228	0.00478				
air	24.9	248	0.00619				
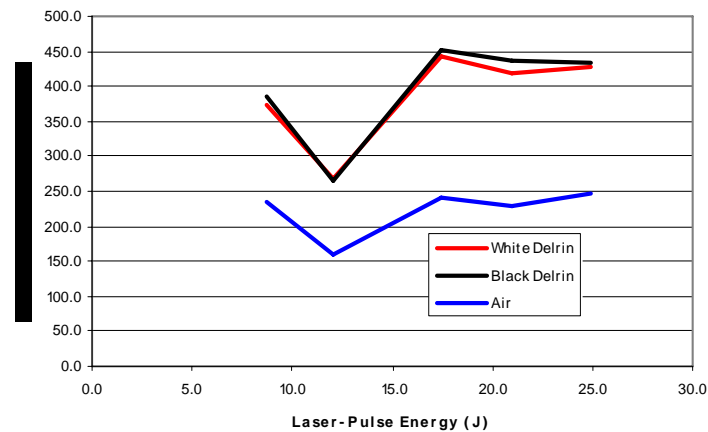
FIGURE 3. Laser-Pulse Energy vs. Coupling Coefficient for Mini-Thruster Experiments
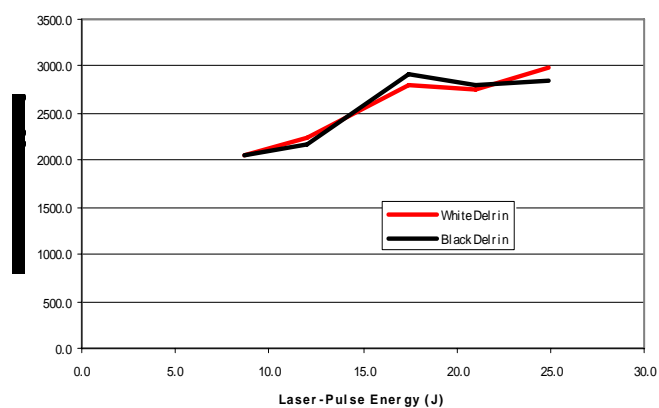
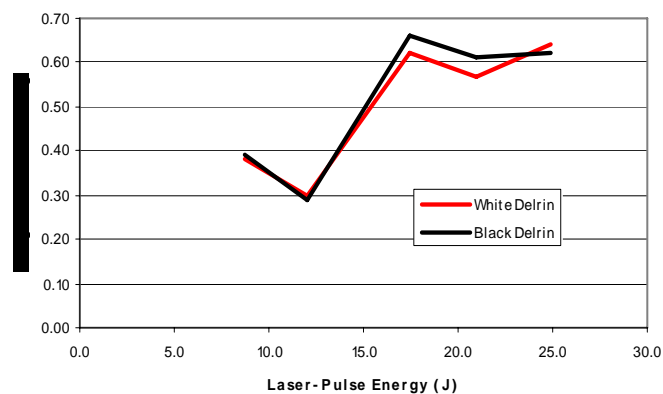**FIGURE 4.** Exhaust Velocity vs. Laser-Pulse Energy for Mini-Thruster Experiments

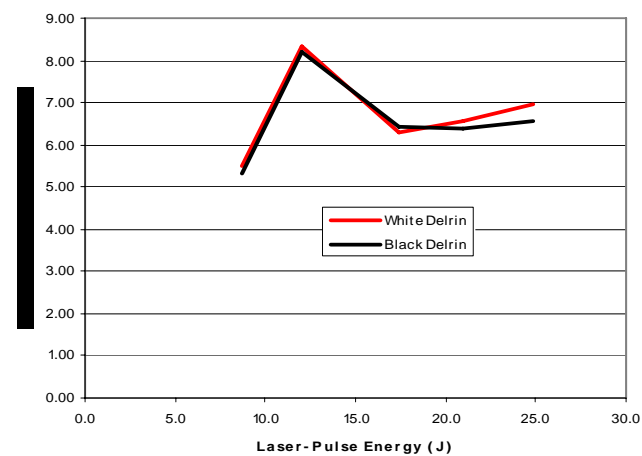**FIGURE 5.** Propulsive Efficiency vs. Laser-Pulse Energy for Mini-Thruster Experiments

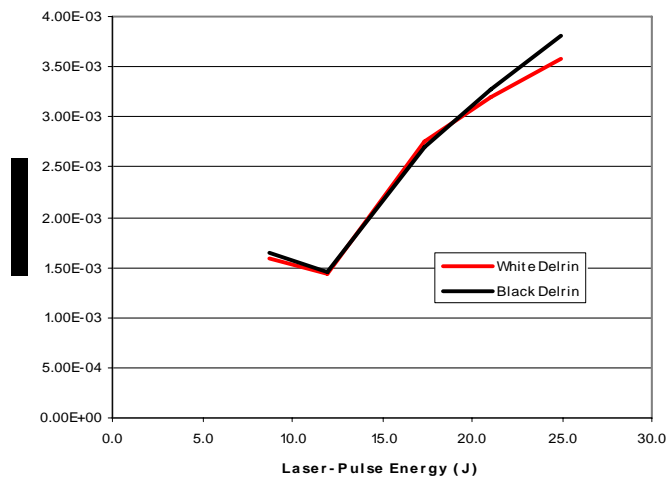**FIGURE 6.** Specific Laser Energy vs. Energy for Mini-Thruster Experiments

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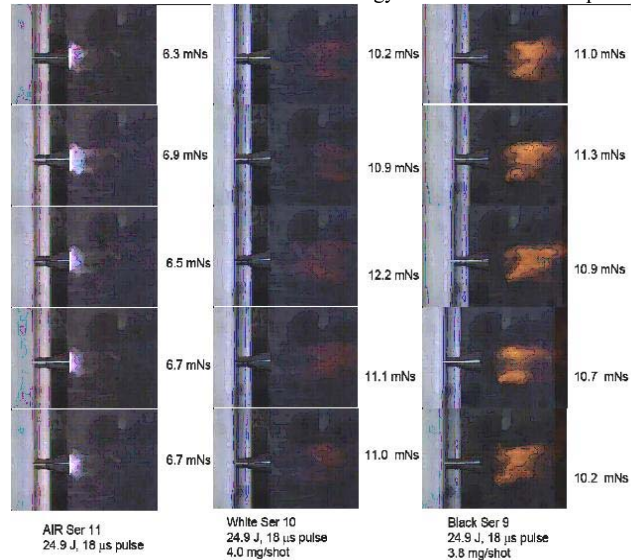**FIGURE 7.** Mass Loss vs. Laser-Pulse Energy for Mini-Thruster Experiments

FIGURE 8. Digital Photos of Mini-Thruster Exhaust Plumes

10 cm Focal Diameter Lightcraft Experiments

The average performance values for the Lightcraft experiments with both white and black Delrin®, air was not evaluated, are shown in Table 2. The values for coupling coefficient, exhaust velocity, efficiency and propellant specific energy due to the laser pulse are all comparable to the values obtained for the mini-thrusters. These results helped validate the concept of "momentum calorimetry" in which heats of formation of energetic propellants are obtained by measurement of the momentum of the jets they produce when they are ablated with known laser energy. The performance of chemically-enhanced laser ablation propellants or other solid propellants may now be inexpensively measured on a small scale. However, the mass

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of propellant ablated per shot is an order of magnitude higher than for the mini-thrusters, as is the laser-pulse energy and resulting impulse.

The resulting trends in Figures 9 – 13 are also extremely different from the mini-thruster experiments. In Figure 9, a graph of the coupling coefficient vs. laser-pulse energy, the coupling coefficient increases over the range from 92 J to 184 J, but then declines as laser energy increases from 184 J to 276 J and then stays relatively constant up to the laser energy of 322 J. The trends for Figures 10 and 11, exhaust velocity and propulsive efficiency vs. laser-pulse energy, show similar trends of varying magnitude. The specific laser energy of the propellant has an opposing trend, shown in Figure 12, which follows in the converse from the analysis discussed in the previous section. The mass loss per shot, depicted in Figure 13, shows a continual increase throughout the range of laser-pulse energies. Figure 14, digital photos of the exhaust plumes for white and black Delrin® in the 10-cm focal diameter Lightcraft, show similar information from the mini-thruster photos. The exhaust plume of the black Delrin® insert is much more pronounced than that of the white. However, the white Delrin® shots are at least noticeable with the Lightcraft experiments.

TABLE 2. Average Performance Values for Lightcraft Experiments

| Prop.	Energy (J)	Cm (N/MW)	I (Ns)	Mass (g)	Ve (m/s)	Eff	El/m (MJ/kg)
White	92.00	251.76	2.32E-02	1.67E-02	1393.49	0.18	5.54
White	184.00	528.65	9.73E-02	4.02E-02	2434.25	0.65	4.60
White	230.00	482.30	1.11E-01	4.74E-02	2342.31	0.57	4.86
White	276.00	414.02	1.14E-01	5.00E-02	2283.82	0.48	5.52
White	322.00	449.57	1.45E-01	6.42E-02	2266.73	0.51	5.04
Black	92.00	246.35	2.27E-02	1.58E-02	1438.07	0.18	5.84
Black	184.00	516.43	9.50E-02	4.29E-02	2216.04	0.57	4.29
Black	230.00	478.52	1.10E-01	4.69E-02	2346.70	0.56	4.90
Black	276.00	424.78	1.17E-01	5.02E-02	2333.60	0.50	5.49
Black	322.00	456.40	1.47E-01	5.98E-02	2458.35	0.56	5.39
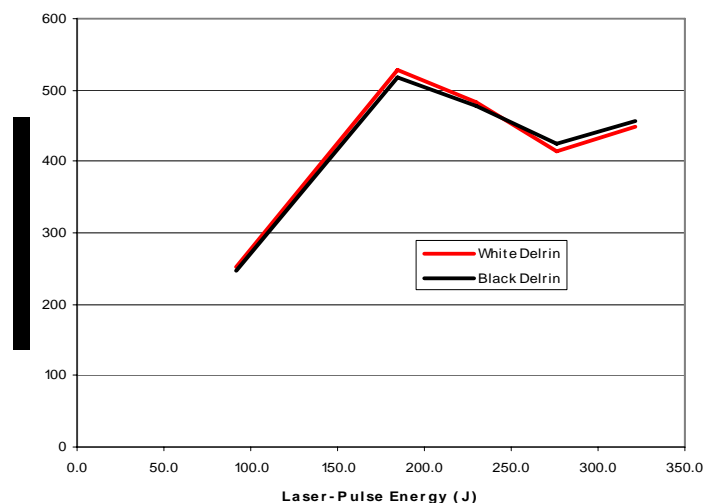
FIGURE 9. Coupling Coefficient vs. Laser-Pulse Energy for Lightcraft Experiments
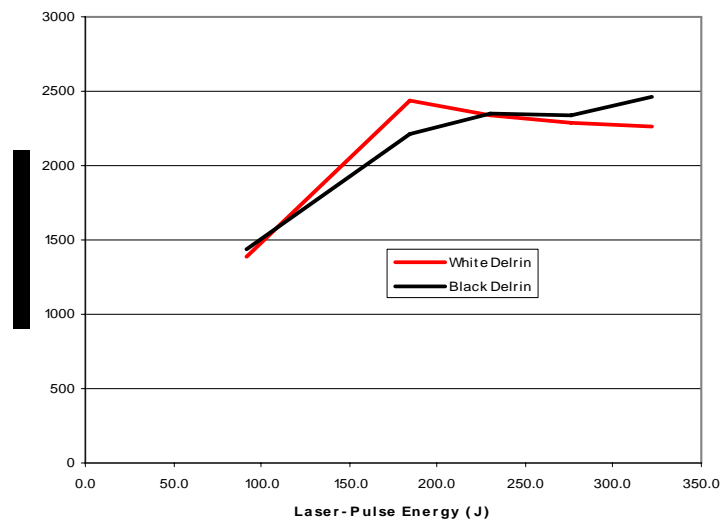
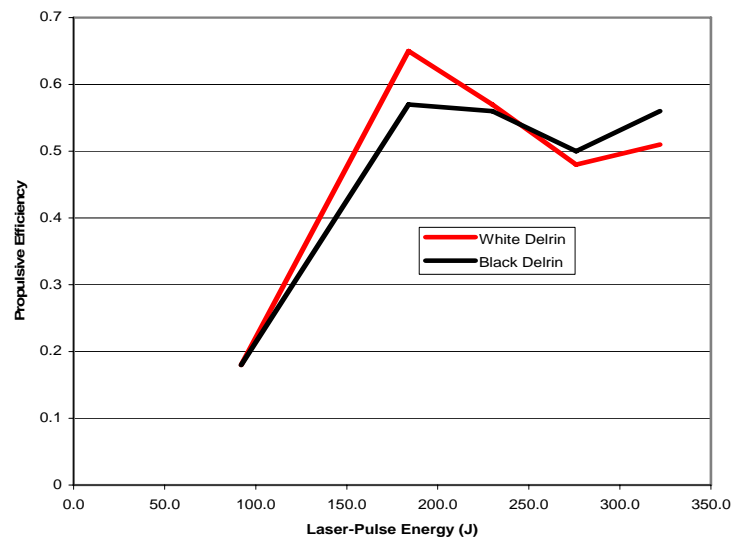**FIGURE 10.** Exhaust Velocity vs. Laser-Pulse Energy for Lightcraft Experiments

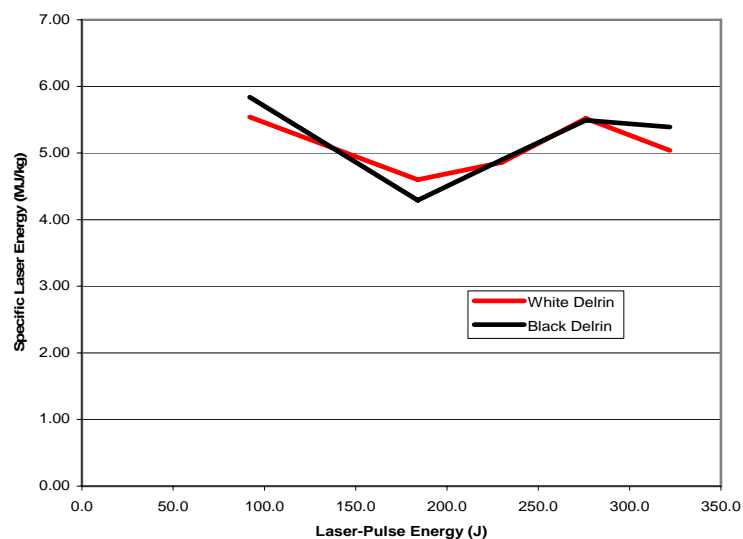**FIGURE 11.** Propulsive Efficiency vs. Laser-Pulse Energy for Lightcraft Experiments

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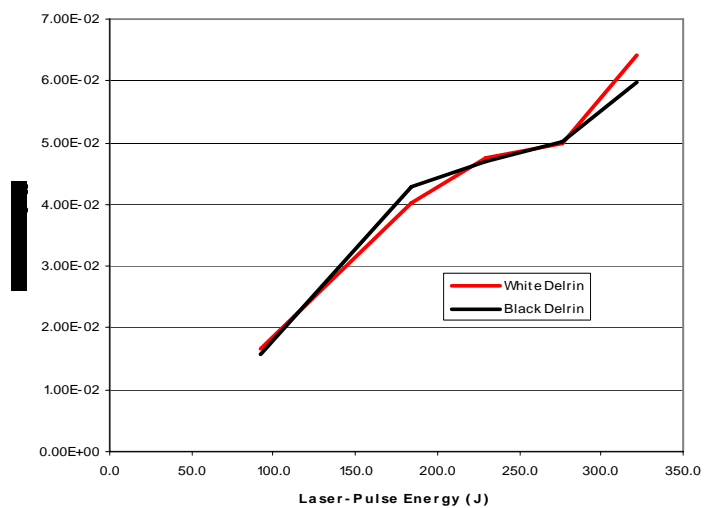**FIGURE 12.** Specific Laser Energy vs. Laser-Pulse Energy for Lightcraft Experiments

FIGURE 13. Mass Loss vs. Laser-Pulse Energy for Lightcraft Experiments
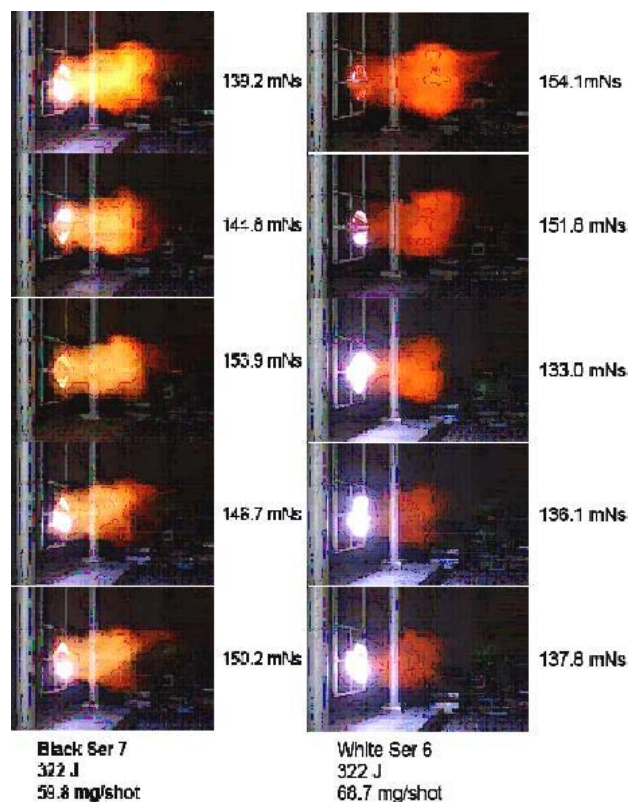
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FIGURE 14. Digital Photos of Lightcraft Exhaust Plumes

CONCLUSIONS AND FUTURE WORK

Several relevant conclusions for the results of the tests with mini-thrusters and the 10-cm focal diameter Lightcraft can be obtained. For instance, the mini-thruster experiments and Lightcraft experiments show nearly identical values of coupling coefficient, exhaust velocity, propulsive efficiency and specific propellant energy. This is in spite of the fact that the irradiance of laser energy on the propellant (laser power per unit surface area of propellant) for the Lightcraft is nearly a factor of 2.5 lower than that of the mini-thruster experiments, 0.8 MW/cm^2 for the Lightcraft to 2.0 MW/cm^2 for the mini-thrusters. However, this is an assumed irradiance based upon the available surface area of propellant in the specimens. Upon investigation of the Lightcraft propellant inserts, it was noticed that there was only a limited amount of propellant surface area being ablated per laser shot. It is possible that this surface area was a factor of 2.5 lower than the available 25 cm^2 for the Lightcraft inserts.

The fact that the performance parameters of the Lightcraft and the mini-thrusters were nearly identical with nearly identical propellant specific energy lends credence to the idea of momentum calorimetry.

Propulsive efficiency numbers for the mini-thrusters were at a maximum of 66%, while the values for the Lightcraft were at a maximum of 65%. Chemical equilibrium

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analysis of the Delrin[®] propellant showed a theoretical limit for the propellant efficiency of 73%. This shows total losses for the mini-thruster geometry of approximately 7% and for the Lightcraft geometry of approximately 8%. This analysis was conducted using NASA's Chemical Equilibrium Analysis (CEA) code [3].

Future work for this study in regard to the mini-thrusters includes a variation of the laser-pulse width of the PLVTS laser from 18 μs to values ranging from 5 μs to 30 μs in an effort to determine the magnitude of exhaust plume shielding during propellant ablation. The laser-pulse energy for the mini-thrusters will also be increased up to 100 J/pulse to determine when or if the propellant is saturated with laser-energy. This will be determined by graphing the impulse vs. the laser-pulse energy. When the graph becomes non-linear, the propellant has become saturated. The time-resolved thrust of the mini-thrusters will be measured piezoelectrically and chemically-enhanced propellants will be developed, evaluated using the NASA CEA code and then the performance will be measured experimentally.

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3. NASA Glenn Research Center, "NASA Chemical Equilibrium with Applications (CEA)," (2005), http://www.grc.nasa.gov/WWW/CEAWeb/, accessed 23 September 2005.